THE *HIFI* HETERODYNE INSTRUMENT FOR *FIRST*: CAPABILITIES AND PERFORMANCE

N. D. Whyborn

Space Research Organisation Netherlands (SRON), PO Box 800, 9700 AV Groningen, The Netherlands.
E-mail: nick@sron.rug.NL; Tel: +31 50 363 4074; Fax: +31 50 363 4033.

ABSTRACT

The Heterodyne Instrument for *FIRST* (*HIFI*) will cover at least the frequency range 492 GHz to 1113 GHz and will provide sensitive observations with resolving powers ranging from less than 5×10^5 to 1.2×10^7. The instrument is optimised for the measurement of weak, broad spectral lines of distant galaxies and for performing fast line surveys of galactic objects. This paper describes the performance, observing modes, and calibration modes of the planned instrument. Companion papers in these *Proceedings* describe the instrument optics, mixers and spectrometer systems.

1. INTRODUCTION

By virtue of its position in space, *FIRST* will observe for the first time the sub-millimetre wavelength transitions of many important chemical species which are presently obscured from ground-based or airborne observations by strong absorption in the Earth's atmosphere. The heterodyne instrument on *FIRST* is intended to provide the capability of very high resolution spectroscopy from 610 µm down to about 250 µm. Two other instruments, the BOL and PHOC described elsewhere in these *Proceedings* [1, 2], will provide medium resolution spectroscopy and photometry over the wavelength interval 85 - 600 µm for this mission. The *FIRST* mission and satellite are described by Pilbratt [3] and Steinz [4] in these *Proceedings*.

A recent review of the scientific drivers for high-resolution spectroscopy at submillimetre wavelengths, with the emphasis on the stellar-interstellar life cycle, has been given by van Dishoek & Helmich [5] (see also these *Proceedings*). They highlight the importance of complete spectral line surveys together with observations of transitions of the species H_2O, O_2 and HD which are difficult or impossible to observe from the ground or aircraft. In conclusion, they recommend continuous frequency coverage from the O_2 line at 487 GHz to the cluster of energetically low-lying water lines around 1200 GHz with, if possible, channels covering important transitions at higher frequencies, e.g. HD at 2674 GHz. Other recommendations include velocity resolutions of order 0.5 km/s or better, and calibration accuracy of better than 10%.

Observations of comets, planets and extragalactic sources place somewhat different requirements on the heterodyne instrument [6, 7]. For comets and absorption lines in planetary atmospheres velocity resolutions down to 50 m/s are desirable, whereas for extragalactic objects it is important to have an intermediate frequency (IF) bandwidth wide enough to include the full rotation curve of the galaxy – up to 1000 km/s is required.

A previous paper [8] describes the evolution and philosophy behind the design of the *HIFI* instrument. Other papers in these *Proceedings* [9, 10, 11] present designs for the optics, mixers and spectrometer systems of the *HIFI* instrument. This paper gives an overview of the instrument architecture and outlines proposed observing and calibration techniques. Finally, the capabilities and performance of the proposed instrument are estimated.

2. INSTRUMENT DESCRIPTION

The *HIFI* instrument will provide continuous frequency coverage of at least 492 GHz to 1113 GHz with a goal of 487 GHz to 1250 GHz. A minimum of four frequency sub-bands will be necessary to cover this frequency range. In addition we plan to include a high frequency channel targeted at the cluster of ortho-water transitions near 1700 GHz. Each of these sub-bands will occupy a different position in the focal plane and thus will not observe the same point on the sky. However, spacecraft resources permitting, it will be possible to operate two sub-bands simultaneously which may be used to advantage to map larger regions at two different frequencies.

Continuous frequency coverage will enable the detection of specific line emission from galaxies with arbitrary redshift. It will also provide complete and uniform line surveys across the sub-millimetre wavelength region allowing the comparison of different transitions of the same species to derive the physical conditions in the emitting region. Full frequency coverage will also allow intercomparison of *FIRST* observations with other ground and airborne observations in atmospheric windows.

The receiver will be optimised for the detection of broad weak line emission, for example from distant galaxies, and for high-speed line surveys of the ISM. To this end the instrument will be equipped with dual-polarisation receivers to maximise sensitivity, while the spectrometer bandwidth will be 4 GHz or more to

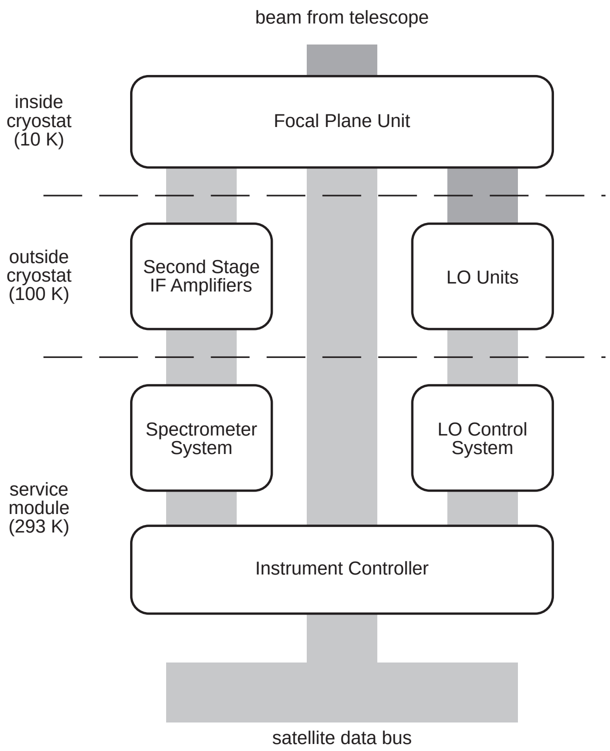

Figure 1 A block diagram of *HIFI*.

increase the speed of line surveys. This will be wide enough to accommodate emission lines of up to 1000 km/s width over most of the frequency range of the instrument.

2.1 Architecture

Figure 1 is a block diagram of the *HIFI* instrument showing schematically the interconnection between the various systems and their placement in the satellite. The instrument consists of 6 units and these are described below.

Focal Plane Unit

The FPU sits inside the *FIRST* cryostat and shares the focal plane with the other two instruments. The area of the focal plane available to the *HIFI* instrument is 80x140 mm corresponding to about 11'x19' on the sky. Relay optics within the FPU divides the beam from the telescope among the 5 dual polarisation mixer units covering each sub-band. A scanning mechanism within the relay optics will provide focal plane chopping and can be used to direct the receiver beam at a black body calibration source determination of the temperature scale.

Each mixer unit contains a pair of mixers accepting both signal polarisations for maximum sensitivity. The mixers themselves will be thermally strapped to the liquid helium tank and operate at a physical temperature of about 2 K whereas the rest of the FPU will be at about 10 K. The optics for injecting the local oscillator signal will be located within each mixer unit together with the IF preamplifiers. SIS mixers will be used up to 1250 GHz with hot-electron bolometer mixers for the high frequency channel.

The mixers will operate in double sideband (DSB) mode without image frequency filtering. This complicates the extraction of a calibrated SSB spectrum from the measurements but simplifies the instrument optics and reduces losses. Since there is no atmosphere, there is no penalty associated with emission in the image sideband. On the contrary, there is a speed advantage of a factor of 2 when performing a frequency survey.

IF System

The IF System amplifies the weak IF signals from the active mixers and distributes them among the spectrometers. Ten parallel IF channels will be required, one for each of the mixers in the FPU, and each will comprise a cascade of 3 amplifiers: one located within the FPU operating at 10 K, one on the outside of the cryostat at 100 K and one in the ambient temperature service module. This gain distribution is required to give maximum sensitivity within the constraints of the cryostat cooling limitations and the required cable lengths. Up to 4 IF channels may operate simultaneously allowing dual-frequency, dual-polarisation observations. The IF centre frequency depends on the mixer technology and the LO injection method used but is expected to be about 10 GHz for the SIS mixers. The instantaneous IF bandwidth will be greater than 4 GHz.

Spectrometer System

The spectrometer system performs the spectral analysis of the IF signals from the mixers. Two resolution bandwidth combinations are required: A wide band spectrometer will be implemented with a suite of acousto optic spectrometers (AOS) giving a frequency resolution of about 1 MHz and a total bandwidth of greater than 8 GHz. A high resolution mode will be implemented either with chirp transform spectrometers (CTS) or digital autocorrelation spectrometers (DACS) types giving a frequency resolution of less than 100 kHz and a total bandwidth of greater than 400 MHz. The system will be flexible allowing the available spectrometer bandwidth to be allocated among 2 to 4 active IF channels.

The spectrometer system will be located in the service module of the spacecraft. It will contain a microcontroller to configure the spectrometers and perform data pre-processing. The spectrometer system will receive commands and synchronisation signals from the main instrument controller and will return spectral data. The satellite will restrict the maximum science telemetry rate to 40 kbps which corresponds to about 2500 spectral channels per second without data compression.

Local Oscillator Unit

The LOU uses a combination of Gunn oscillators and cascaded varactor frequency multipliers to generate the high frequency local oscillator signals required to pump the mixers. Since the tuning range of currently available sub-mm LO sources is limited, a pair of sources will be required to cover the tuning range of each mixer sub-band. The LOU is located on the outside wall of the cryostat and will operate at a temperature of about 100 K. The LO signals are injected into the FPU through a window in the cryostat vacuum vessel.

Local Oscillator Control Unit

The LOCU contains the phase-lock electronics to control the frequency of the local oscillators. It will also provide the necessary bias and control voltages to operate the frequency multiplier chains and any associated mechanisms. The medium term frequency stability and line-width of the LO signals must be much less than 1 part in 10^7 to enable observations at velocity resolutions down to 50 m/s. However, the long term frequency stability is not so critical since this can be monitored and corrections applied off-line.

The LOCU will be located in the ambient temperature service module of the satellite. It is planned that the LOCU will contain its own microcontroller to take care of tuning and monitoring of the LO receiving its commands from the instrument controller.

Instrument Control Unit

The ICU provides the overall control of the instrument. It will receive commands through the satellite data bus, interpret them and pass on instructions to the LOCU and spectrometer systems. It will also provide control functions for the FPU by supplying the bias for the mixers and IF preamplifiers and driving the chopper and calibration unit. Another important function of the ICU will be the synchronisation of the observing process within the instrument and with the satellite attitude control system. In addition the ICU will distribute power to the other subsystems of the *HIFI* instrument.

The ICU will combine data from the spectrometers with housekeeping data before transmission to the satellite's on-board data handling system. The *HIFI*, and ICU in particular, must be designed to operate fully autonomously since *FIRST* will operate for up to 21 hours per day without contact with the ground. In this respect it is important that the instrument can detect faults and take corrective action automatically.

3. OPERATION

3.1 Observing Modes

Three major observing modes are foreseen

- deep, point-source integrations,
- line surveys, and
- on-the-fly mapping.

For observations of a single point the technique of dual beamswitching will be used with the instrument focal plane chopper providing beamswitching with a throw of 3 arcmin. at up to 1 Hz. By repointing the satellite the source will be placed alternately in the two beams to cancel instrument baseline offsets, important for the detection of broad, weak lines.

For performing line surveys the local oscillator frequency will be stepped across the desired frequency range while making short integrations. The step size will be less than the IF bandwidth to give smooth continuous frequency coverage. By tracking spectral features in both sidebands of the mixer it will be possible to deconvolve the DSB measurements to generate an unaliased spectrum using a variation of CLEAN [12, 13], or maximum entropy techniques [14]. See Schilke et al [15] for a discussion of the application of these techniques to *FIRST* observations.

For mapping sources larger than the beamswitch throw, the technique of mapping-on-the-fly will be used. In this mode the telescope will make a raster scan across the source while simultaneously chopping with the focal plane chopper. The source structure can then be recovered using algorithms such as those described by Emerson et al [16] and Richer [17].

3.2 Internal Temperature Calibration

The radiometer's effective DSB system temperature and gain in counts per Kelvin will be measured by chopping between blank sky and an internal black-body source at a variable temperature of between 10 to 80 K. For the estimated system temperatures given below, and neglecting systematic effects, the temperature difference will be sufficient to allow a calibration accuracy of about 1% for a 1 s calibration measurement.

3.3 Flux Calibration

Observations of calibration sources of known flux or brightness temperature will be used to determine the telescope beam and aperture efficiencies. Table 1 lists the estimated antenna temperatures for the planetary and asteroidal continuum flux calibrators commonly used in the sub-mm wavelength region [18, 19, 20, 21, 22]. Due to spacecraft constraints, the range of allowed sun elongation angles (angle between the telescope boresight and sun direction) will be limited to 90 ±15° and this will preclude the observation of Venus, the

Table 1 Estimated antenna temperatures, T_A^*, of observable planetary sub-mm calibrators calculated for a solar elongation angle of 90° and assuming a *FIRST* telescope diameter of 3.5 m. The planetary brightness temperatures, T_B, are estimated from measurements in the literature [18, 19, 20, 21, 22].

planet	disc size/"	T_B/K 500GHz	T_B/K 1THz	T_A^*/K 500GHz	T_A^*/K 1THz
Mars	4.2	210	220	6.9	26
Ceres	0.27	140	140	0.010	0.039
Vesta	0.18	180	180	0.018	0.067
Jupiter	18	160	145	74	114
Saturn	8.3	128	108	14.9	36
Uranus	1.8	75	64	0.43	1.14
Neptune	1.1	75	62	0.161	0.42

Moon, and any object inside the Earth's orbit. It also implies that opportunities for observing Mars and the outer planets will be severely restricted: any given planet will be observable during two periods every year or so (every 2 years in the case of Mars) for a total of less than 10% of the time.

4. PERFORMANCE

4.1 Instrument Sensitivity

Zmuidzinas [23] and van de Stadt et al [24] have given recent reviews of the sensitivity of receivers in the sub-mm wavelength region. Current SIS mixers provide DSB receiver temperatures of 80 K at 500 GHz rising rapidly between 700 and 850 GHz to about 750 K at 1 THz. Recent results with HEB mixers include DSB receiver noise temperatures of 1900 K at 1.3 THz and 2500 - 3000 K at 2.5 THz [25]. To estimate the performance of the *HIFI* instrument, we will take these values for the mixer sensitivities and ignore the probable improvement in performance between now and the construction of the receiver.

In order to arrive at the SSB system sensitivity one should take account of coupling losses in the instrument, the telescope efficiency, focal plane chopping, and DSB mixer operation. A conservative estimate for the coupling losses within instrument is 20% or 1 dB. This comprises aberrations and other coupling losses together with ohmic losses in the optical components.

The *FIRST* telescope primary diameter will probably be 3.5 m. However, the secondary will be undersized by about 10% to ensure that it forms the pupil over the telescope field of view which is essential to minimise the background for the direct detection systems. This limits the telescope useful geometric aperture to about 3.2 m but results in most spill-over falling on cold sky. The total telescope wave-front error will be less than 12 μm r.m.s. resulting in a scattering loss of 6% at 1 THz and 19% at 1.8 THz. However, we take the main beam and aperture efficiencies to be 90% and 60% independent of frequency.

Table 2 The expected mixer DSB receiver noise temperatures with corresponding SSB system noise temperatures and 5σ flux detection limits of *HIFI* at 3 frequencies (see text for details).

	500 GHz	1 THz	1.8 THz
T_{RX}(DSB, mixer)/K	80	800	2500
T_{sys}(SSB)/K	470	4700	15000
$5\sigma F(R=10^5)/(\mathrm{Wm^{-2}})$	4×10^{-19}	6×10^{-18}	3×10^{-17}
$5\sigma F(R=10^4)/(\mathrm{Wm^{-2}})$	1.4×10^{-18}	2×10^{-17}	8×10^{-17}

The focal plane chopper will be used for most observations and this reduces the observing efficiency and increases the effective system temperature. The *HIFI* chopper will have a dead-time of less than 10% increasing the system temperature by a factor of 2.1.

For spectral line observations the relevant measure of system sensitivity is the single sideband noise temperature. Assuming a mixer sideband ratio of unity, as expected for a broad-band, fixed-tuned mixer, the SSB noise temperature is double that of the DSB value.

Table 2 lists the expected effective system noise temperatures at 500 GHz, 1 THz and 1.8 THz taking into account the above factors. Also listed are the 5σ flux detection limits for a spectral resolving power of $R=10^5$ and an integration time of 1 hour. Note that we ignore the √2 improvement in sensitivity to be obtained when observing an unpolarised source by co-adding the measurements from both polarisations.

4.2 Observing Speed

Taking the instrument sensitivity outlined above, we can calculate the expected observing performance for three illustrative cases: a deep, point-source integration, a line survey, and mapping. As before we have not taken into account the possibility of co-adding polarisation channels to obtain higher sensitivity nor do we make any allowance for calibration and other overheads.

Deep Integration

For this case we will take a spectral resolution of $R=10^4$ (30 km/s velocity resolution). A 1 hour integration time gives the 5σ flux detection limits listed in Table 2.

Line Survey

We consider a spectral line survey to a specific noise level with a fixed frequency resolution of 1 MHz and with a spectrometer bandwidth of 4 GHz. We assume single-frequency operation – i.e. only one sub-band is operational at any one time. The 1.8 THz channel is

Table 3 The mapping speed in arcmin² per hour to achieve the stated noise level in a fully sampled map.

	500 GHz	1 THz	1.8 THz
noise level, σT^*/K	0.1	0.3	1
mapping speed /(arcmin^{2}hr^{-1})	170	9	5

ignored since the likely tuning range is highly uncertain at this time. Note that for line surveys the effective IF bandwidth is doubled since both sidebands are measured simultaneously.

12 hours of observing is required achieve a uniform 1σ noise floor of 30 mK for a survey over 492 - 800 GHz. A similar survey to 100 mK noise level over the frequency interval 800 - 1113 GHz will take 18 hours.

Mapping Speed

For this case we calculate the mapping speed to achieve a specific noise level per (Nyquist sampled) pixel with a resolving power of R=10^5. The calculation assumes dual-beam mapping is used and neglects any tracking overheads. The mapping speed in arcmin^2 per hour to achieve a given noise level are listed in Table 3.

4.3 Comparison with *SOFIA*

To illustrate the benefit of observing above the atmosphere we have compared the sensitivity of HIFI with an identical receiver operating on the planned *SOFIA* airborne observatory [26]. We have computed the flux detection limits for *SOFIA* taking the planned telescope characteristics from Becklin [26] together with modelled atmospheric transmission data supplied by M. Haas (private communication). The model atmosphere used is one for good observing conditions, namely a flight altitude of 41000 ft, a telescope elevation of 40°, and a zenith water vapour column of 5 µm. The results for spectral resolving powers of R=10^3 and R=10^5 are plotted in Figure 2 and show the effect of the forest of telluric absorption lines.

5. CONCLUSIONS

We have outlined the heterodyne instrument which is proposed for FIRST and estimated its likely performance. According to the current mission schedule, the instrument will be launched at the end of 2005 and will provide the first high resolution view of the sub-mm universe unaffected by absorption in the Earth's atmosphere.

6. ACKNOWLEDGEMENTS

It is a pleasure to acknowledge the contributions of the members of the *HIFI* Group who are:

A. Räisänen: HUT, Finland.
A. Baudry, P. Cais: Bordeaux Observatory, France.
J.-C. Villegier: CEA Grenoble, France.
E. Caux, M. Giard, L. Ravera: CESR Toulouse, France.
C. Goldstein, G. Serra: CNES, France.
M. Carter, B. Lazaref, A. Karpov: IRAM, France.
P. Cruvellier: Institute Gassendi, France.
M. Deleuil, A. Laloge, R. Malina: LAS Marseille, France.
G. Beaudin, P. Encrenaz, A. Lecacheux, C. Rosolen, M. Salez: Observatoire de Paris, France.
H.-W. Hübers, F. Lura, H.-P. Röser, G. Schwaab: DLR Berlin, Germany.
K. Jacobs, C. Honingh, R. Schieder, J. Stutzki, G. Winnewisser: Köln University, Germany.
P. Hartogh: MPIfAe Lindau, Germany.
R. Güsten, P. Schilke: MPIfR Bonn, Germany.
P. Zimmermann: Radiometer Physics, Germany.
A. Murphy: St. Patrick's College Maynooth, Ireland.
E. Natale, G. Tofani: CNR Firenze, Italy.
R. Orfei, P. Saraceno: Frascatti, Italy.
C. van Dijkhuizen, M. W. M. de Graauw, T. de Jong, W. Luinge, P. Roelfsema, H. van de Stadt, P. Wesselius, N.D. Whyborn, K. Wildeman: SRON, Netherlands.

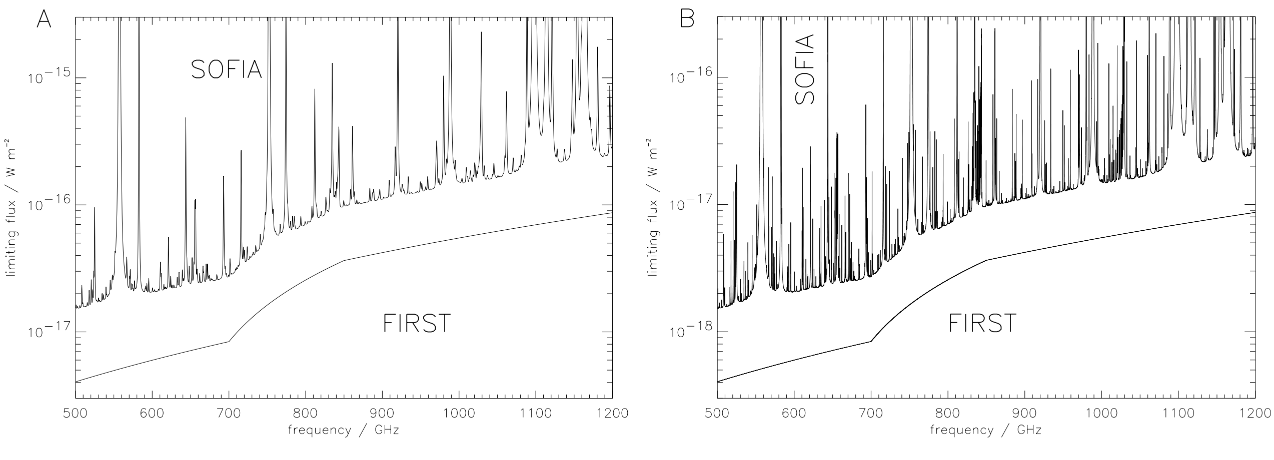

Figure 2 A comparison of the 5σ spectral flux density detection limits of *FIRST* and *SOFIA* for resolving powers of A) R=10^3, and B) R=10^5 (see text for details).

J. Cernicharo, D. Gallego, J. Martin-Pintado: Centro Astronomico Yebes, Spain.
V. Belitsky, R. Booth, E. Kollberg, S. Torchinsky: Chalmers Univ. of Technology, Sweden.
U. Frisk: SSC, Sweden.
L. Nord: Stockholm Observatory, Sweden.
S. Withington, R. Hills: MRAO Cambridge, UK.
G. White: QMW, UK.
B. Ellison, D. Matheson: RAL, UK.
T. Phillips, J. Zmuidzinas: CALTECH, USA.
N. Erickson: FCRAO UMass, USA.
M. Mahoney, E. Cohen, M. Frerking, W. Gray, C. Lawrence, H. Leduc, R. McGrath, P. Siegel: JPL Pasadena, USA.
R. Blundell: SAO Cambridge, USA
A. Harris: Univ. of Maryland, USA.

We thank Mike Haas for supplying the model atmosphere transmission data. We also thank the *FIRST* project team at ESA for their assistance, in particular J. Cornelisse, C. Jewell, T. Paßvogel, G. Pilbratt, H. Schaap, and J. Steinz.

7. REFERENCES

1. Griffin, M. J. 1997, The design of a bolometer instrument for FIRST, in *Proc. ESA Symp., "The Far Infrared and Submillimetre Universe"*, ESA SP-401 (this volume).
2. Poglitsch, A. 1997, An optimised photoconductor instrument for FIRST, in *Proc. ESA Symp., "The Far Infrared and Submillimetre Universe"*, ESA SP-401 (this volume).
3. Pilbratt, G. 1997, The FIRST mission, in *Proc. ESA Symp., "The Far Infrared and Submillimetre Universe"*, ESA SP-401 (this volume).
4. Steinz, J. A. 1997, FIRST project status, in *Proc. ESA Symp., "The Far Infrared and Submillimetre Universe"*, ESA SP-401 (this volume).
5. van Dishoek, E. F. & Helmich, F. P. 1996, Scientific drivers for future high-resolution far-infrared spectroscopy in space, in *Proc. 30th ESLAB Symp., "Submillimetre and Far-Infrared Space Instrumentation"*, ed. E. J. Rolfe, ESA SP-388, pp. 3-12.
6. Crovisier, J. & Bockelée-Morvan, D. 1997, Comets at submillimetre wavelengths, in *Proc. ESA Symp., "The Far Infrared and Submillimetre Universe"*, ESA SP-401 (this volume).
7. Encrenaz, T. 1997, Observations of planets and satellites in the far-infrared and submillimetre range, in *Proc. ESA Symp., "The Far Infrared and Submillimetre Universe"*, ESA SP-401 (this volume).
8. Whyborn, N. D. 1996, A heterodyne instrument for FIRST: HIFI, in *Proc. 30th ESLAB Symp., "Submillimetre and Far-Infrared Space Instrumentation"*, ed. E. J. Rolfe, ESA SP-388, pp. 215-218.
9. Torchinsky, S. A. & Belitsky, V. Yu. 1997, Optical architecture for the heterodyne instrument on FIRST, in *Proc. ESA Symp., "The Far Infrared and Submillimetre Universe"*, ESA SP-401 (this volume).
10. van de Stadt, H. et al 1997, Detectors for the heterodyne spectrometer of FIRST, in *Proc. ESA Symp., "The Far Infrared and Submillimetre Universe"*, ESA SP-401 (this volume).
11. Rosolen, C. & Lecacheux, A. 1997, IF processing and back-ends: An optimised configuration for the HET instrument on FIRST, in *Proc. ESA Symp., "The Far Infrared and Submillimetre Universe"*, ESA SP-401 (this volume).
12. Groesbeck, T. D. et al 1994, *Astrophys. J. Supp.*, **94**, 147.
13. Schilke, P. et al 1997, *Astrophys. J. Supp.*, **108**, 301.
14. Sutton, E. C. et al 1995, *Astrophys. J. Supp.*, **97**, 455.
15. Schilke, P. et al 1997, FIRST wide band submillimetre line surveys, in *Proc. ESA Symp., "The Far Infrared and Submillimetre Universe"*, ESA SP-401 (this volume).
16. Emerson, D. T. et al 1979, *Ast. Astrophys.*, **76**, 92.
17. Richer, J. S. 1992, *Mon. Not. R. astr. Soc.*, **254**, 165.
18. Ulich, B. L. 1981, *Ast. J.*, **86**, 1619.
19. Ulich, B. L. et al 1984, *Icarus*, **60**, 590.
20. Hildebrand et al 1985, *Icarus*, **64**, 64.
21. Griffin et al 1986, *Icarus*, **65**, 244.
22. Griffin, M.J., Orton, G.S. 1993, *Icarus*, **105**, 537.
23. Zmuidzinas, J. 1996, Recent progress in submillimeter heterodyne receiver development, in *Proc. 30th ESLAB Symp., "Submillimetre and Far-Infrared Space Instrumentation"*, ed. E. J. Rolfe, ESA SP-388, pp. 151-154.
24. van de Stadt, H. et al 1996, A sensitive 1 THz SIS waveguide mixer, in *Proc. 30th ESLAB Symp., "Submillimetre and Far-Infrared Space Instrumentation"*, ed. E. J. Rolfe, ESA SP-388, pp. 231-235.
25. McGrath, W. R. et al 1997, Superconductive hot electron mixers with ultra-wide RF bandwidth for heterodyne receiver applications up to 3 THz, in *Proc. ESA Symp., "The Far Infrared and Submillimetre Universe"*, ESA SP-401 (this volume).
26. Becklin, E. 1997, Stratospheric observatory for infrared astronomy (SOFIA), in *Proc. ESA Symp., "The Far Infrared and Submillimetre Universe"*, ESA SP-401 (this volume).